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Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/Capabilities Perspective)

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Abstract

In the last two decades substantial advances have been made in the understanding of the scientific basis of urban climates. These are reviewed here with attention to sustainability of cities, applications that use climate information, and scientific understanding in relation to measurements and modelling. Consideration is given from street (micro) scale to neighbourhood (local) to city and region (meso) scale. Those areas where improvements are needed in the next decade to ensure more sustainable cities are identified. High-priority recommendations are made in the following six strategic areas: observations, data, understanding, modelling, tools and education. These include the need for more operational urban measurement stations and networks; for an international data archive to aid translation of research findings into design tools, along with guidelines for different climate zones and land uses; to develop methods to analyse atmospheric data measured above complex urban surfaces; to improve short-range, high-resolution numerical prediction of weather, air quality and chemical dispersion through improved modelling of the biogeophysical features of the urban land surface; to improve education about urban meteorology; and to encourage communication across scientific disciplines at a range of spatial and temporal scales.

Keywords: Urban climate; modelling; observations; human-environment interactions; adaptation; mitigation; built environment

1. Introduction

1.1 Sensitivity of cities to climate variability and change

Cities and their inhabitants are key drivers of global climatic change. The large and ever increasing fraction of the world's population that lives in cities uses a disproportionate share of resources and produces climate-altering atmospheric pollutants. Cities affect greenhouse gas sources and sinks both directly and indirectly. They are the main source of anthropogenic carbon dioxide emissions due to the burning of fossil fuel for heating and cooling, industrial processing, transport of people and goods and so forth. While the exact values are subject to debate, it is widely held that more than 70 per cent of anthropogenic carbon emissions can be attributed to cities, with the wealthy cities located in developed countries in the northern hemisphere as the main emitters [1][2]. (Svirejeva-Hopkins et al. [3] place this value in excess of 90 per cent.) Cities are also sources of many anthropogenic pollutants emitted to the atmosphere, with consequences for both local air quality and for regional and global atmospheric chemistry and its consequences for climate change [4]. Moreover, the demand for goods and resources by city dwellers, both historically and today, is a major driver of regional land-use change such as deforestation, surface pavements, buildings and drainage patterns.

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Cities are also sensitive to climate variability and change. They have the highest population densities (over 50 per cent of the world's population is concentrated in less than 3 per cent of the land area) and many urban residents are poor and especially vulnerable to extreme events and climatic variability. Population density is even greater in low elevation coastal zones (LECZs; <10 m above sea level), 60 per cent of which are now urbanized and particularly vulnerable. Of all cities with populations greater than 5 million people, 65 per cent are located in LECZs, and of the 183 countries with people living in the LECZs, 130 have their largest urban area extending into the zone [5]. Since coastal locations are vulnerable to sea-level rise and destructive meteorological events such as tropical storms (hurricanes, typhoons), large-scale climate change and variability will influence coastal urban populations disproportionately. Moreover, cities have already changed their own climates. For example, temperatures are higher, ventilation is weaker and air quality is poorer, which further compounds sensitivity to future global changes.

This document identifies current capabilities to observe and predict urban atmospheric processes across a range of spatial scales. It provides the scientific underpinning actions to allow cities to contribute to the mitigation of, and become more resilient in adapting to, local climate change caused by cities themselves and to the consequences of global climate change. Attention focuses on the key influences of cities on climate and the challenges to understanding that remain to provide direction in tackling climate-related risks. Firstly, the scales essential to understand and analyse the urban climate and weather are defined. Secondly, the applications that use urban meteorological information are discussed, starting from the smallest scale. Thirdly, current scientific capabilities and understanding based on observations and modelling are reviewed

1.2 Scales and surface description

An appreciation of spatial scale is key to understanding urban climates, observations and modelling. At global and regional scales, a city's climate, and its effects on climate, are influenced by its geographical setting: latitude, continentality, openness to synoptic events, proximity to water, surrounding topography, etc. These factors also influence the design of a city (for example, building styles) and the behaviours and activities of its inhabitants (demands for heating, cooling, etc). Cities themselves are a source of buoyant, warm, polluted air that can modify precipitation patterns, especially downwind [6][7] and air quality and atmospheric chemistry thousands of kilometres away from the source. Within a city, neighbourhoods with similar land use and land cover, generate distinct local-scale climates (102–104 m). These are a function of the urban morphology, built materials, amounts of vegetation, and human activity (amounts of heat, water, etc., released). A simple urban-based climate classification system can distinguish areas by aerodynamic roughness, mean aspect ratio and impermeable surface cover [8][9]. At smaller spatial scales (100–101 m), a person in a city experiences a range of conditions: sunlit or shaded areas of street; channelling or no wind; influence of a park or shade trees. At this scale, key features that need to be included in surface description are: (a) surface roughness length, because it influences wind flow; (b) impervious surface fraction, as it is key to energy partitioning between heat and moisture exchanges; (c) sky view factor as it influences solar access and radiative cooling; (d) thermal admittance as it modulates heating and cooling cycles of materials; (e) albedo as it influences surface heat absorption and(f) anthropogenic heat flux as it is an additional source of energy for the system [10].

2. Applications

There are a wide range of users who need information about urban weather and climate for managing and planning sustainable cities. The following outlines the current applications from the building to the larger spatial scales.

2.1 Architectural design and urban planning

Cities and buildings tend to be planned and designed following historical precedents that are attuned to the particular climatic and cultural environments (for example, Butti and Perlin [11]; Acharya [12]; Reardon et al.[13]). However, in the recent past many building developments have been insensitive to climate. They usually require large energy resources to allow the inhabitants to be comfortable in both/either winter and/or summer, a practice that is not sustainable. This has particularly been the case with large commercial buildings. The best of modern climate-sensitive design and planning responds to concerns for energy efficiency and sustainability with "good design" [14]. Here, current design options for two climate regions are discussed where appropriate design can ameliorate otherwise severe environmental conditions that negatively impact human comfort, health and productivity.

2.1.1 Climate sensitive design in hot-arid regions

Low atmospheric humidity allows a relatively wide range of air temperatures to be acceptable in urban spaces, provided sufficient air movement exists and radiant sources of thermal stress are controlled. Typically clear skies and high surface albedo amplify the need for protection from solar radiation, in both its direct and indirect forms (that is, diffuse and reflected from ground or wall surfaces). Given the high heat capacity typical of urban pavement and building materials, absorbed solar radiation may be translated into substantial heat stress due to terrestrial long-wave radiation emitted from adjacent hot surfaces (as well as from the atmosphere). Thus the potential benefits of deep shading (that is, protection of canyon facets as well as of pedestrians) are commonly observed in compact urban forms with narrow streets and enclosed courtyards. This is typical of traditional construction in many hot-arid locations [15][16][17][18].

Deeply incised streets and courtyards can result in the trapping of short-wave and long-wave radiation, thereby increasing the net all-wave radiation and storage of heat [19]. Further, the increased frictional drag in narrow street districts impairs ventilation. Together these controls can lead to elevated air temperatures and low wind speeds, despite the benefit of internal shading from the geometry [20]. Model results of the effects of canyon geometry on pedestrian energy exchange show a dependence on street axis orientation and the Height/Width (H/W) ratio [21]. Thermal stress can be reduced by high H/W ratios in north-south streets, provided that the building and paving materials have sufficiently high heat capacity to store excess heat and radiate it away during the cooler night-time hours [22][23].

Microclimate in arid cities can also be ameliorated by landscape and building treatments including shade to pedestrians and paved surfaces: overhangs, colonnades, plant canopies and trellises [16][24][25]. Extensive lawns or similar open ground cover may not be practical because they require the use of scarce water resources. With water-sensitive urban design, water can be reused to allow for some of the cooling benefits [26]. Responsive desert building design includes: selective orientation and treatment of window openings for maximal solar gain in winter and protection in summer; use of multi-layered walls and roofs combining thermal insulation and internal thermal mass; night ventilation and evaporative cooling; compact envelope forms and high-albedo materials to moderate conductive heat transfer; earth-integration; and the shading of roofs and transition spaces such as porches and patios [27].

2.1.2 Climate sensitive design in warm-humid regions

Without cool winters, urban populations in tropical regions may be exposed year-round to the negative consequences of urban warmth. Ventilation is critical in the tropics. Designs, through manipulation of geometry (height and width of buildings, building and street orientation and street width) have to consider ways to increase wind penetration and provide shade during thermally critical times of the day to enhance thermal comfort [28][29][30][31]. The high zenith sun angles in the tropics require a combination of building heights and geometry with elements such as canopies, awnings and vegetation. The time when shading is beneficial depends on the general weather pattern in the tropics, the typical dimensions of city blocks in a particular city and people's activity patterns [32].

The abundance of natural vegetation in the humid tropics can be utilized to provide shade and evaporative cooling. At high zenith angles roofs are the most thermally active building surface. Vegetated roofs can enhance thermal comfort by insulating buildings, and can improve air quality, reduce storm water runoff intensity, improve run-off water quality and create new habitat for wildlife, and hence have been used extensively in many climatic regions [33][34][35][36][37][38][39][40][41][42][43]. Similarly, vegetation provides thermal benefits, removes air pollutants and absorbs CO_2, relieves human stress, mitigates run-off intensity during storms and modulates urban flood events.

2.2 Human comfort and health

It has only become recognized recently that heat has such a devastating impact on human health and heat is considered a deadly weather-related phenomena over much of the developed world. For example, during the summer of 2003, an excessive heat event (EHE) killed over 15 000 people in France alone; in Paris there were at least three days when the baseline mortality of 50 people more than tripled [44][45]. It has been estimated that there are on average 1 100 heat-related deaths per year in Australian cities [46]. In February 2009 there was an unprecedented EHE with six consecutive days with temperature maximums above 40°C in Adelaide and three consecutive days when temperatures exceeded 43°C in Melbourne.

Excessive heat events have also led to a large number of excess deaths in Seoul [47] and Chicago. Under future warmer climates a dramatic increase in heat-related mortality is predicted [48]. The most vulnerable locations for heat-related problems are where heatwaves occur at irregular intervals, and where summer climates are highly variable. High latitude cities are more vulnerable to EHE impacts than low latitude cities. Cities like New York, Philadelphia, Paris, Rome, Athens and Shanghai have suffered many deaths during excessive heat events. Over the last 15 years, several techniques have been devised to issue heat/health-related warnings to assist in the development of urban plans to enhance public awareness and to lessen the impact of heat, and to check the effectiveness of heat warning systems [49][50][51][52][53].

2.3 Forecasting urban weather, hazards, air quality and climate

Cities impact, to varying degrees, virtually all weather variables that have a direct impact on humans: temperature, humidity, winds, sunshine and precipitation. Apart from important effects of the urban heat island (UHI, Section 3) on human comfort, morbidity and mortality, the UHI is also intimately connected to demand and use of energy in cities. In turn, energy use generates greenhouse gas emissions that contribute to climate change. Thus, cities are both major contributors to the causes of global change and in a warming world are adversely impacted by it. The interaction between the land surface and the atmosphere has a significant impact on the evolution of near-surface weather. As summarized in Section 3.3 the surface energy fluxes of an urban area differ greatly from those of surrounding rural areas. These impacts on surface–atmosphere exchange need to be explicitly considered in models forecasting local weather for cities. For example, it is well known that urban areas have an impact on the mesoscale air flow around a city and may affect the direction of convective storms [54].

Operational global weather and climate models fail to resolve cities, there are few routine urban observations and global models are typically verified with synoptic upper-air soundings [55]. These realities pose large challenges to the urban modelling community. Besides the basic requirement for accurate weather information for cities throughout the world, it is possible that urban fractions within grid-boxes of global models can have an important impact on the larger circulation, a topic which has received little attention to date. However, given improvements in computer resources, it is now possible to resolve urban areas in mesoscale models. Several urban physics schemes are now available for use in operational models (for example, Masson [56]; Martilli et al.[57]; Best [58]). Their incorporation requires a balance between complexity and computational requirements due to the required timeliness of operational forecasts. Recent research shows that even a basic representation of urban areas can lead to significant improvement in urban temperature forecasts [58]. Forward-looking national meteorological services are on the cusp of forecasting urban weather at scales of a few kilometres or less.

Heating, ventilation and air conditioning (HVAC) accounts for 40–60 per cent of the energy used in commercial and residential buildings in the United States. The HVAC energy use is lower in the developing world and trends in China [59] are indicative of the scale of the looming problem. Buildings account for 30 per cent of the final energy consumed in China and up to a third of this is expended in air conditioning in urban areas. Energy use is especially sensitive to temperature in the hot summer months and in southern regions. Electricity demand for cooling increases 3–5 per cent for every 1°C increase in air temperature above approximately 23°C ±1°C [60]. This implies that a 5°C UHI can increase the rate of urban electric power consumption for cooling by

15–25 per cent above that used in surrounding rural areas. During extreme heat events, a further consequence of the UHI is to stress the electric grid owing to the increased peak power demand. This is an expensive stress upon urban infrastructure and leads to brown outs (for example, Australian, United States cities). Accurate short-range forecasting of temperatures throughout the day within cities is important not only to mitigate heat stress impacts, but to ensure that electric utilities can meet the demand for power (which is required in large part for air conditioning) and in a cost-effective manner. In this way, there is a strong and very important interdependence among ambient temperature, city size, human comfort and demand for electricity.

Besides heat stress, forecasting weather in the urban zone is important to the prediction and mitigation of other multiple but disparate hazards, such as adverse air quality, dispersion of toxic chemicals and precipitation. Urban air quality prediction has been pursued for about four decades, but it has only been in the last few years that urban air quality predictions have been directly coupled with weather prediction [61]. Poor air quality in cities means large concentrations of people are potentially exposed to a wide range of harmful pollutants emitted by transport and industry. Cities also modify their ambient weather (especially winds, turbulence, radiation, mixing height and temperature) in ways that often negatively affect the dispersion, transformation and concentration of those pollutants.

In addition to conventional air pollutants, toxic chemicals and agents may be emitted from industrial and transport accidents and occasionally deliberate acts of terrorism and biomass burning (heating in winter, controlled or prescribed burning to mitigate bush fire hazards, bush fires themselves). Because of the complex morphology of the urban environment, the transport and diffusion of these chemicals can be extremely complicated and challenging to quantify, especially if they are released within street canyons or in the roughness sub-layer (RSL, typically less than two times the mean building height H) around building arrays, trees, etc. Pollutants emitted at street level can recirculate within the street canyon with the consequence that pollutant concentrations on the leeward side (upwind, relative to the roof-level wind field) of the street can be twice as great as those on the windward side. The concentration patterns are even more complicated when the pollution is dispersed in a field of buildings (for example, Hanna et al. [62][63]; Klein et al.[64]).

2.4 Practical applications of urban atmospheric information

Urban managers need to consider these complexities when developing air pollution control strategies or issuing air pollution alerts. Emergency managers are further challenged when dealing with accidental or terrorist releases or bush fires (at the rural/urban interface) because the species of the chemical or radioactive material, its rate of release and the effective height of that release (owing to buoyancy considerations) may be only partly known or not known at all. It is also likely that the local meteorology will also not be sufficiently known and in some cases the exact location and time of the release will not be known. Challenging as this scenario is, progress is being made in the development of methods to aid emergency services calculate quick estimates [65].

Other short-term needs for weather forecasts in urban areas relate to urban precipitation events. The ability to predict the intensity and patterns of thunderstorms is essential to protecting populations from flooding risks, recovering from power outages, warning about paths and timing of tornadoes or other dangerous winds, managing storm water volumes and water treatment. These have health and safety ramifications as well as economic and political consequences. The ability of transport networks (road, rail, airport, metros) to effectively manage and operate in urban areas is often dependent on the ability to forecast weather conditions. These systems are vulnerable to a wide range of conditions including fog, snow, ice, strong winds and high temperatures. Forecasting systems have been developed for aspects of the transportation system but there is increasing demand to improve these both in terms of the lead times and the spatial resolution. Improved abilities to forecast these not only allows better functioning and safety of a city but also can reduce costs of management (for example, reduced salt use, improved skills scores so that correct warnings reduce labour costs).

Urban areas, as already noted, are often located close to coastal locations. The implications of this are that there is vulnerability to variability of sea level at both short and long timescales. Short-term storm surges can have catastrophic effects that need to be predicted to allow evacuation for safety without causing false closures at great costs. But long-term changes in the frequency of high sea levels means that planning to protect areas, through relocating parts of cities, building barriers (for example, London Thames Barrier) is critical, as is the improved capability to downscale climate predictions to urban areas. This also implies that the climate predictions that are used for downscaling need to have urban areas in their long-term predictions [66][67]. It should be noted that the models used in the most recent climate prediction did not include urban characteristics but the next generation of model runs will include this capability. Currently, data that are downscaled may or may not take urban characteristics into account.

High latitude cities benefit from additional urban warmth which reduces energy needs in winter. High latitude cities are also susceptible to climate change as any changes in permafrost will have significant influences on the urban infrastructure. The need to be able to appropriately plan, design, build and retrofit for future climatic conditions to prevent failure of the built infrastructure from melting is essential. There are similar infrastructure vulnerabilities associated with the rates of groundwater recharge (reduced or increased). Variations in precipitation, irrigation and evaporation rates that are modified in urban areas need to be included in models (that is, changes in landscape and the response of the urban hydro-climatic processes). In coastal locations the groundwater recharge, if not managed appropriately, can also have saltwater intrusion with additional damaging effects.

All cities are dependent on their surroundings for potable water. Regional climate change predictions are therefore also important to ensure that the resources needed for the sustainable operation of the city can be maintained. Obviously, with increasing city size the regional impact becomes larger. Mega-cities have proportionally larger demands for resources to sustain them in socially, politically, economically and healthily viable ways in terms of inputs (energy, water, food) and also outputs (waste, air quality, water quality). There is a need to ensure that water-sensitive urban design is incorporated with meteorological information at the appropriate scale for building- to city-scale design and planning.

Planning to adapt to climate change in cities requires locally relevant information of the impacts of climate change on appropriate timescales – generally years to a few decades. This requires knowledge of how the climate responds at the scale of cities, how climate is affected by human influences at other scales (the urban effects documented here), the role of natural climate variability and changes in the near future. (For nearer-term projections, the greenhouse-forced climate change signal is smaller and less easy to distinguish from noise.) As building have an expected life that takes them well into periods when the climate is expected to have changed, it is important that the designs of new developments are taking the anticipated extreme values into consideration (http://www.knmi.nl/samenw/ensembles_rt5/etccdi/debiltmeeting).

3. Urban processes and observational capabilities

3.1 Thermal

The thermal environment of urban areas has received widespread attention because of the urban heat island effect – a general warming of urbanized areas relative to their non-urbanized surroundings (for example, Voogt [68]; Souch and Grimmond [69]; Yow [70]). Understanding the urban thermal environment requires knowledge of temperature of the surface, air and the subsurface. Determination of true urban effects is not possible in most cases, because pre-urban measurements do not exist and other landscape changes have occurred [71].

3.1.1 Urban air temperatures

Air temperature measurements using direct techniques (thermocouples, thermistors) are relatively simple and well established. Routine measurements of urban temperature are not always made and there is no standard practice for such measurements or their integration into applications. Recent studies have used many stations to provide better spatial resolution for urban temperature analysis (for example, Kim and Baik [72]; Pigeon et al. [73]; Hinkel and Nelson [74]; Hidalgo et al.[75]). This is made possible by low cost, miniaturized data loggers. Selection of observation sites is often logistically constrained, but model simulations have been used successfully to define suitable network locations [73]. Careful siting, exposure and documentation of metadata are essential to ensure data from different cities are comparable and are suitable to test models [76]. Measurements made in urban parks or just above rooftops (where sensor height is close to the roof) should be avoided because they constitute relatively anomalous urban surfaces. If urban to non-urban differences are required, perhaps to define the magnitude of the urban heat island, the choice of the non-urban site also is very important (Hawkins et al. [77]; Sakakibara and Owa [78]; Stewart and Oke [79]). The field is hampered by the lack of a standard practice to calculate urban heat island strength (for example, Fortuniak et al. [80]).

Understanding urban canopy air temperatures and the associated canopy layer heat island depends on recognition of the footprint of the measurement. Unfortunately, this is a non-trivial task given the convoluted form of the canopy layer. From the extensive literature it is known that the canopy layer heat island is (a) largest at night and may often be negative (relatively cooler compared to non-urban surroundings) during the day; (b) best expressed under anticyclonic conditions and decreases with wind speed and cloud cover; and (c) controlled by urban surface structures (for example, canyon H/W ratio, where H is the building height and W is mean spacing between buildings), thermal admittance, vegetation cover and moisture that impart spatial variability to the urban temperature field. The exact spatial and temporal configuration of the canopy layer temperature of a given city is sensitive to the climate, topography, time of day, season and specific attributes of the structure, cover, fabric and operations of the city. Improving the generalization of urban heat island understanding thus depends in part on appropriately categorizing urban areas according to these factors [76]. No universal relation of the heat island exists.

Attribution of urban temperature to specific controls remains somewhat qualitative, but geometry and thermal properties have been shown to be almost equal in creating a heat island [81][82][83][84][85]. Anthropogenic heat plays a variable role that increases in importance in more densely developed districts and/or in high latitude/winter season situations (for example, Ichinose et al. [86]; Hinkel and Nelson [74]; Hart and Sailor [87]). Spatial variations in canopy layer temperature can be observed via mobile traverses or assessed with a dense network of fixed sites, but there is no simple, general scheme to estimate temperatures within the urban area.

Within the urban boundary layer (UBL), routine air temperatures may be measured in situ by sensors or on tall towers, while research temperature measurements may be taken using tethered or free-flying balloons or sensors attached to an aircraft and by remote sensing. Much less work is available on the urban boundary layer UHI compared to the canopy layer UHI.

3.1.2 Urban surface temperatures

The spatial variability of surface temperature (distinct from near-surface air temperature) in urban areas has been well described using thermal infrared measurements from ground, airborne and satellite-based instruments, and its relation to land cover/land use is well documented [88][89][90][91][92][93]. Urban surface temperatures have received attention because they are considered important for planning and mitigation of urban temperatures for purposes related to human comfort and energy use [94][95][96]. There is potential for confusion when users fail to identify the surface represented in the data or needed in the application [76], although guidelines on how to properly characterize the surface are available [97]. Because of complications introduced by the presence of cloud, nearly all satellite data are restricted to clear, or mostly clear, conditions.

The variables that affect surface temperature are well known but because they often vary at microscales, their influence at satellite-observed pixel scale is less well understood [98]. Sub-pixel examination such as spectral mixture analysis has shown promise and remotely derived measures of both vegetation and impervious surface cover can be used to help explain spatial patterns [91][93][99][100].

Thermal anisotropy complicates the interpretation of remotely sensed surface temperature because only a subset of the complete urban surface is viewed and is typically averaged at length scales that do not easily allow retrieval of individual components [101][102][103][104]. Relatively few studies have explicitly examined urban emissivity, although some analyses assess it from temperature–emissivity separation algorithms [105][106][107][108].

The magnitude and seasonal variation of surface urban heat islands are reasonably well known, albeit for the restricted times, atmospheric conditions and viewing geometry of these sensors [88][109][110][111][112][113]. Recognition of the three-dimensional surface, possible variations in emissivity and an appropriate definition and/or control for what defines the "rural" area tend to be lacking.

Relating surface temperatures to air temperatures is complicated by different source areas (or footprints) for radiation instruments, thermometers and instruments to measure the turbulent components of the surface energy balance, but progress has been made in understanding of how dry urban areas exchange sensible heat with the atmosphere through scale-model analysis and field projects that couple energy balance measurements with remote sensing (for example, Pearlmutter et al.[19]; Kanda et al.[114]; Kawai et al.[115]; Xu et al.[107]). However, there remains potential to misinterpret measurements of the surface temperature when used to characterize the canopy-layer UHI.

3.1.3 Urban subsurface temperatures

Subsurface temperatures in urban areas also experience warming (for example, Dettwiller [116]; Ferguson and Woodbury [117][118]; Tanaguchi et al. [119]). This has implications for geothermal heating and cooling, carbon exchange processes between the soil and atmosphere and the chemical and microbiological characteristics of groundwater. Observations are made using thermometers in boreholes or wells. The relation with surface processes is complex and not yet well described but there is greater subsurface warming in areas with dense (and long-term) urban development.

3.2 Wind and turbulence

The extreme heterogeneity of urban landscapes and the inherent difficulties of taking measurements in built-up areas have limited the number of high quality urban observations of flow and turbulence [120]. As a result progress in developing a consistent picture of flow and turbulent transport in urban areas has been relatively slow. Laboratory studies (Section 4.1) and numerical simulations (Section 4.3) are used to compensate for the lack of full-scale observations.

Urban turbulence measurements before 2000 have been summarized [120]. Much of the earliest work concentrated on flow properties well above roof level to avoid the large spatial variability close to buildings and within the roughness sub-layer. Results confirmed the applicability of traditional surface layer scaling laws (Monin-Obukhov similarity) in the urban environment above the buildings. This is often used in the absence of another unifying framework to analyse and present urban turbulence data, but it has been noted that the empirical coefficients are different from those of the homogeneous surface layer found at extensive rural sites [120].

Measurements within and above urban canyons demonstrate the shear stress generally increases with height to a peak value near or above the top of the canyon [121][122][123][124][125][126][127][128]. These results have been used to define transitions from the RSL to the inertial sub-layer (ISL) and affirm that Monin-Obukhov similarity concepts can be applied if the scaling velocity u* is related to the peak shear stress [129][130].

Over the last decade, comprehensive urban measurement campaigns have been conducted in several cities on different continents and over a range of land uses (for example, Cooke et al.[131]; Allwine et al.[132][133]; Arnold et al.[134]; Longley et al.[135]; Venkatram et al. [136]; Mestayer et al. [137]; Rotach et al.[138]; Eliasson et al.[139]; Offerle et al.[140]; Kanda et al. [114]; Hanna et al.[63]). There have also been observations of flow and turbulence over outdoor physical scale models using shipping containers and concrete blocks to mimic urban building arrays and to overcome observational constraints present in real urban settings (for example, Biltoft [141]; Inagaki and Kanda [142]). Results indicate that flow is often dominated by vortices developing at the edges of buildings and intersections and that high-momentum air at upper levels is mixed down to street level in the wake of tall buildings. Canopy layer flow and turbulence patterns are primarily dynamically driven by the mean wind at the average roof level, and atmospheric stability has only an indirect influence on canopy layer flow [143][144]. Investigations of the role of coherent structures on turbulent transfer processes and budgets of turbulent kinetic energy (TKE) in the urban RSL have shown that turbulent heat and momentum transfer is dominated by sweeps in the upper part of the canopy layer and only higher above the roofs, near the transition between the RSL and ISL, do ejections start to dominate the transport (similar to vegetation canopies) (Feigenwinter and Vogt [145]; Salmond et al. [146]; Christen et al.[147]; Nelson et al. [143][144]; Christen et al.[128]). The roof layer is found to be a region of high TKE production but low dissipation and consequently has significant turbulent transport.

Sonic anemometers are now the standard instrument but are increasingly joined by remote sensors such as scintillometers, sodars and lidars to measure mean and turbulence parameters close to the surface and throughout the urban boundary layer at relatively high spatial resolution (Roth et al. [148]; Lagouarde et al.[149]; Barlow et al. [150]; Calhoun et al. [151]; Davis et al.[152]).

3.3 Energy partitioning

The available energy at any location, urban or rural, to evaporate water or to heat the air or ground, depends on the radiation balance:

$$Q^* = K^* + L^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad \text{Units: } W\,m^{-2} \qquad (1)$$

where Q* is the net all-wave radiation, K the short wave or solar fluxes, L the long wave or terrestrial fluxes, and the arrows indicate whether the flow of energy is towards (↓) or away (↑) from the surface. The net all-wave radiation, plus the anthropogenic heat flux (QF) due to the heat released by combustion of fuels, drive non-radiative exchanges between the surface and the atmosphere [153]:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad \text{Units: } W\,m^{-2} \qquad (2)$$

where Q_H is the turbulent sensible heat flux (heating the air), Q_E is the turbulent latent heat flux (linked to evaporation, E, [mm of water] through the latent heat of vaporization [Section 3.5]), ΔQS is the net flux of heat stored (heating of the urban fabric), and ΔQ_A is the net horizontal advective heat flux through the surface layer of the urban volume.

Again, attention to scale, as noted in Section 1.2, is critical to ensure that the observations of surface energy balance fluxes are representative of the area of interest. The main approaches to measuring the turbulent fluxes are eddy covariance and more recently scintillometery. Several observational campaigns have been conducted in the last decade in urban areas. While this is a major step forward, the results cannot yet be said to be sufficiently comprehensive to be representative of all climate zones nor of all synoptic conditions.

Latitude controls the incoming short-wave radiation (K↓) at the top of the atmosphere but the synoptic and regional setting influences the probability of cloud and the nature of air pollution within the region, thus affecting solar radiation received at the surface. Aerosol concentrations alter scattering, the relative amounts of direct and diffuse radiation received, the transmissivity of the atmosphere and the short-wave flux received at the surface. High aerosol loading reduces the amount of incoming solar radiation in most tropical megacities by >20 W m^{-2} [154]. Reduced solar radiation in turn slows photochemical processes, reducing the formation of secondary pollutants in urban areas [155]. On the other hand, urban heat islands (increased air temperatures) accelerate photochemical processes and modify dispersion characteristics [112][113][156]157].

Surface materials and morphology alter the albedo (reflectivity) of the urban surface. Lighter materials tend to have higher albedos than darker building fabrics. Building materials (paints, roofing covers, etc), which have higher albedos, have been developed to reduce the radiative loading of urban areas and thus mitigate urban heat islands [158][159]. These so-called cool materials no longer have to be light coloured and are being used for all elements in the city, roofs and walls, and for vehicles as well [160]. If the surface materials are kept constant, a larger height-to-width ratio results in a lower bulk albedo for an urban array [161][162].

The net long-wave radiation depends on both the atmospheric (for L↓) and surface conditions (L↑). The urban atmosphere is both polluted and warm. In general the warmth of the urban heat island dominates and L↓ is enhanced compared to that over the countryside. The surface materials and urban structure influence the surface temperature and emissivity. The trapping of long-wave radiation in areas with low sky view factors (large H/W ratios) results in a lower net long-wave loss (L*) at street level.

While urban influences on individual radiative fluxes can be significant, and can vary substantially at the microscale or local scale, overall the effects tend to balance and the net all-wave radiative flux in cities tends to be close to that in nearby rural settings [163].

The turbulent sensible heat flux is driven by the net available energy, the gradient in air temperature between the surface and the air above it and the ability of the air to transport the energy away from the warm location (towards or away from the surface). Typically in cities, especially in summertime and in densely built up areas, unstable conditions prevail during daytime and mildly unstable or neutral conditions at night. At high latitudes in winter, or at night in areas of low building density, transport of sensible heat towards the surface may occur at night. The airflow regime, which is influenced by the surface morphology, can enhance or dampen heat transport to and from the surface. The typical diurnal course of the turbulent sensible heat flux is related to the nature of the building fabric (a key control on the storage heat flux) and the available moisture including the fraction of green space (key controls on the latent heat flux).

Typically the storage heat flux is considerably larger in an urban area than its rural surroundings [164]. This flux is the net uptake or release of energy (per unit area and time) by sensible heat changes in the urban canopy air layer, buildings, vegetation and the ground. Key characteristics that influence the size of the storage heat flux are the surface materials, the urban structure and the resulting thermal mass. In general, urban surface materials have good ability to accept, conduct and diffuse heat into (and out of) the urban fabric. The flux is therefore significant because there is a large mass to heat up and cool down, plus there is a large surface area when vertical faces are included. In a rural area the soil heat flux may be about 5 per cent of the net all-wave radiation; in cities this value may be up to 40–50 per cent. Moreover, there is a distinctive diurnal trend in cities. The storage heat flux is typically larger in the morning, before solar noon, as heat is transported into the building volume. However, by mid- to late afternoon heat is transferred back to the surface and released into the atmosphere, which helps to maintain a positive turbulent sensible heat flux and hence unstable stratification in cities in the evening and at night. This large heat store also helps to increase the energy available for long-wave radiative exchange and is a contributor to the characteristically warmer air temperature.

Since conduction is not as efficient a process as convection, typically there are steep thermal gradients into the urban fabric relative to the surface temperature. Very high surface temperatures are frequently observed in cities (for example, by thermal remote sensing), but away from surfaces (for example, inside building cavities or air temperatures) the range of temperatures are considerably less. Thus the thermal characteristics (heat capacity, thickness of layers, density) of built materials provide opportunities for architects, planners and engineers to manipulate energy exchanges both internally and externally for a building, thereby affecting urban climates at the microscale and local scale.

The complexity of the urban surface makes the storage heat flux difficult to observe. Two approaches have primarily been taken through (a) calculation as a residual of the energy balance, and (b) intensive sampling of the temperatures of all surface facets then calculation using heat conduction equations. Both approaches have the possibility to contain large measurement errors but recent comparisons of the two methods show consistency in their results [140][165].

Advection results from spatial differences of surface characteristics, for example in surface temperature, moisture availability or roughness. The city's setting (for example, coastal or valley), dictates the magnitude and direction of these exchanges at scales larger than the city. Within the city, the patchiness of urban surfaces (at the property or neighbourhood scale) affects horizontal energy exchanges and mixing. For example, patchy vegetation may give contrasts of air temperature and moisture in close proximity, which can result in a net horizontal flux that cools warmer areas. On a hot summer's day, well-irrigated grass next to a road or other paved surface will result in such advection. The effects of this on spatial variability of evapotranspiration rates in parks have been documented [166]. Such patchiness and advection have important implications for the stress of vegetation in urban settings. However, the size of the advective fluxes between neighbourhoods is not well documented.

3.4 Anthropogenic emissions (heat, water, carbon dioxide)

Energy consuming activities in cities contribute to anthropogenic emissions of waste heat and carbon dioxide (CO_2) within the boundaries of the city and at the regional power plants that serve the city. These emissions result from energy use in buildings, transportation, manufacturing and other industry. The relative magnitude of each source varies as a function of the thermal climate of the city, the relative size of a city's manufacturing sector and socio-economic and cultural factors that vary between cities and countries such as the mode of personal transport, the timing of the workday and the source of fuels.

Based on aggregate energy consumption data [167][168] in developed nations, energy use is relatively equally distributed among the building, transport and manufacturing sectors, respectively. The way in which energy consumption translates into anthropogenic emissions, however, is different for each sector. For vehicles, the burning of gasoline or diesel fuel results in direct emission of heat and CO_2 at the point of use of the vehicles and this results in a distinct diurnal profile with local peaks corresponding to morning and evening traffic rush hours. In contrast, energy consumption in the building and manufacturing sectors has both a direct local emissions component (within cities) and a primary emissions component at the source (the power plant delivering electricity to these sectors) which depends on the source of the power (wind, hydroelectric, fossil fuel or nuclear).

3.4.1 Estimating the magnitude of the anthropogenic heat flux (QF)

Many early studies equated end-use of energy in buildings with direct emission of sensible heat into the urban environment [86][169]. There are two factors that may make estimates inaccurate. Firstly, larger commercial buildings in many cities rely on some form of evaporative cooling. As a result, any heat removed from a building (including the waste heat from energy use) leaves the building as a combination of sensible and latent heat fluxes. Secondly, heat rejected from buildings can be significantly different from energy consumption due to environmental loads (for example, direct solar radiation transmitted through windows). Such environmental loads are ejected by the air conditioning system regardless of the energy consumption within the building. Accurate anthropogenic emission estimates from buildings therefore require a whole-building energy balance.

Over the past several decades researchers have tried to estimate anthropogenic heat emissions in cities [170][171]. These estimates range from simple annual estimates of city-wide heat emission to detailed lot-level measurements of energy consumption. Building energy simulation tools can estimate actual sensible and latent heat emission from cooling, heating and ventilation systems in buildings [172][173]. The different approaches to modelling QF clearly show that the magnitude of the flux depends upon the scale of analysis. While a city-wide estimate of anthropogenic heating may suggest the value is 10s of W m^{-2}, it is possible at the scale of a city block or an individual building for the value to rise above 1 000 W m^{-2} [86].

There are very few cases, however, where researchers attempted to physically measure anthropogenic heat and/or moisture emissions. This is due in part to the variety of sources of waste heat and moisture in the urban environment and the challenges associated with measuring these emissions. Some researchers have used eddy covariance to estimate the total heat or moisture flux from urban canyons and then have combined these estimates with measurements and estimates of the individual flux terms in the energy budget to estimate anthropogenic heating as a residual in the energy balance [140]. While useful, this approach is also an indirect measurement of anthropogenic flux subject to errors from the uncertainties in each of the measured flux terms.

3.4.2 Estimating urban CO_2 emissions

Direct sources of urban carbon dioxide emissions include transport, households, the human body, soils and vegetation (the total urban ecosystem). The first attempts to quantify the role of these sources on the carbon budget have largely focused on inventories of emissions typically constructed through a bottom-up aggregation process that accounts for emission factors (often derived from laboratory or specific field measurements), activity levels (obtained from local authorities, specific surveys, roadway maps, aerial photographs, geographic statistics, etc.) and source distributions. In this way, emissions are computed through emission factors and activity levels (production, consumed fuel, distance travelled, etc.) for each emission source (using emission processors, such as SMOKE (Sparse Matrix Operator Kernel Emissions Modeling System. Center for Environmental Modeling for Policy Development (CEMPD), University of North Carolina, Chapel Hill (http://www.smoke-model.org/index.cfm)). Complete inventories must include emissions from mobile (for example, vehicles), area (for example, residences) point (for example, industries) and biogenic sources (for example, soils, vegetation). (See, for example, Nowak [174]; Jo and McPherson [175]; Mensink et al. [176].)

Alternatively, surface–atmosphere exchanges of CO_2 can be measured directly using micrometeorological techniques, notably eddy covariance equipment mounted on tall towers. Such direct measurements can be used to evaluate emission inventories and have the advantage of including all major industrial and mobile, minor commercial and residential sources from a specific region. These data are, however, still relatively rare. The most striking features common to most reported measurements are the positive (directed away from the surface) flux values during most hours of the day [153][177][178][179][180][181]. Thus cities are typically sources of CO_2, unlike vegetated areas where photosynthesis results in assimilation (uptake) of CO_2 during daytime hours. Flux peaks, often visible in the early morning and late afternoon, may exceed 10 μmol m^{-2} s^{-1}, and correspond to peaks in traffic volume during the rush hour periods. The magnitude of the fluxes in the middle of the day is strongly modulated by the amount of vegetation. Strong localized sources such as main road intersections can cause directional variability in the flux which may require careful source area analysis.

The few long-term studies available show seasonal variability and the expected increase of CO_2 fluxes during the winter months caused by higher emissions from increased space heating and reduced uptake by vegetation outside the growing season [178][180].

Seasonal differences can be very large in cold climate regions. For example in Copenhagen average monthly winter values are up to six times larger than summer emissions at a central city site [182].

3.5 Moisture, water and hydrology

Since the turbulent latent heat flux (Q_E) is the energy equivalent of the evaporation term in the water balance, the size of this flux influences not only the partitioning of the convective energy fluxes (Bowen ratio, $\beta = Q_H/Q_E$) and therefore many of the urban climate features observed, but also other fluxes in the water balance such as groundwater recharge.

The turbulent latent heat flux depends on the availability of moisture at the surface, the sign and size of the surface–air humidity gradient and the ability of the atmosphere to transport moisture. Unlike the spatial pattern of surface temperatures in a city where differences are always present, albeit with varying contrasts, in urban environments it is possible to have areas/times where there is no surface moisture (for example, a sealed parking lot with no vegetation after a long period with no rain) and areas where it is freely available (for example, irrigated parks, detention ponds). Human activities such as street cleaning, allowing/banning/regulating garden irrigation, etc., can significantly modify water availability and thus rates of Q_E. When irrigation bans are instituted to conserve water, the rate of evapotranspiration drops accordingly. Typically the densely developed central area of a city has little vegetation, and residential areas much more, a difference that is reflected in their patterns of Q_E. However, even in the driest urban settings such as central Mexico City and Ouagadougou water is present and evaporation is measurable [140][183].

Of course, evaporation is also influenced by the frequency and intensity of precipitation events, and the efficiency of methods used to detain or rapidly drain rainwater. In many cities water is retained in neighbourhood detention ponds (particularly common in the United States) or recycled into local wetlands, or held on individual properties (becoming common in Australia) to irrigate vegetation or for internal water use. Under very humid conditions small moisture gradients can limit evaporation rates. Immediately following a rain shower, or in the early morning after dewfall, there can be large latent heat flux values for a short period of time (for example, Richards and Oke [184]; Richards [185]).

Depending on the climate and season, precipitation occurs in different forms including rain, hail and snow. It is important to observe and record the amount, form and intensity of precipitation in cities because of its relevance to management and safety issues such as flooding, hail damage, drought and the need for road clearance. Until recently observations from tipping bucket raingauges have been the primary source of precipitation data but now new sensors are becoming available including a sensitive pan. Point measurements do not afford sufficient spatial, and in certain circumstances temporal, resolution so new approaches are in use. These include radar which provides spatial information but cannot be used alone due to uncertainties about its accuracy [186][187]. These uncertainties stem from errors due to surface clutter, beam attenuation and measurement height relative to the surface, among other factors [188]. Satellite-based observations using the Tropical Rainfall Measuring Mission (TRMM) have been used to study the extent of rainfall modification [189]. The role of urban areas in modifying rainfall continues to be disputed [6][190]. There is a need for more extensive measurements in urban areas.

There have been very few studies of urban dew although enhanced moisture within the urban atmosphere as a result of anthropogenic activity suggests the potential for accumulation. Significant amounts (0.1 and 0.3 mm day^{-1}) were found using scale models in Vancouver, Canada, on nights with optimal conditions for dew formation especially on roofs and exposed grass [191].

The spatial patterns of atmospheric moisture in cities are influenced by those of temperature, and by the surface moisture and latent heat fluxes. Typically, urban areas are described as having an atmospheric urban moisture deficit compared to surrounding rural areas (for example, studies cited in Kuttler et al. [192]). This is because of less vegetation, the greater air temperatures (which increase the saturation vapour pressure) and drainage networks designed to rapidly remove precipitation from urban areas. Nevertheless, urban air can contain greater moisture at night and in the winter, especially at high latitudes. Care needs to be taken when comparing moisture metrics as there are a number of different measures (for example, relative humidity, specific humidity, dew point temperature, absolute humidity, vapour pressure) and these may be a function of other variables (for example, pressure, temperature) as well as actual moisture content change in the air.

4. Prediction and modelling capabilities

4.1 Scale models

Scale models using a wide variety of experimental facilities and measurement techniques have contributed significantly to understanding the urban atmosphere. Most commonly urban flow, turbulence and dispersion phenomena have been simulated in wind tunnels and water flumes or outdoors over idealized arrays of building-like obstacles. Attention has focused on the RSL where practical measurement issues limit comprehensive full-scale investigations. Most laboratory studies have been conducted under neutral stratification and/or strong flow when mechanical turbulence dominates.

Several scale-model studies have focused on development of morphometric methods to relate roughness length and displacement height to characteristics of building structures (for example, Bottema [193][194]; Macdonald et al. [195]). These methods have been reviewed and their merits evaluated using both full-scale and scale-model data [196]. Extensive wind-tunnel datasets of flow and dispersion characteristics inside and above different types of building arrangements have been used to develop a semi-empirical urban dispersion model and to develop a classification scheme for urban building zones [196][197].

The recent development of computational fluid dynamics (CFD) codes for cities (Section 4.3) has spurred the need for high-resolution laboratory datasets to evaluate them [198][199][200][201][202]. Different types of simulation domains and approaches are available for street canyon studies (for example, Vardoulakis et al. [203], Kastner-Klein et al. [204]) Of particular interest are street canyons that are characterized by long buildings flanking narrow streets, for which the flow and mixing inside the street is driven by a recirculation-type quasi-two-dimensional vortex [203].

Both wind-tunnel and full-scale observations, however, show that vortices that develop at the lateral building edges can extend over significant portions of street canyons and the more simple two-dimensional flow regimes often depicted are not necessarily typical [64][127][143][144]. Studies have demonstrated that small-scale features such as roof shape, the presence and placement of trees or moving traffic can significantly impact street canyon ventilation rates [64][199][205][206][207][208][209].

Similarity considerations imply that only a small range of model scales can be investigated in wind tunnels given their typical size. The few studies of realistic models of cities highlight that variability of the building height has a strong influence on the flow and turbulence structure within the urban RSL [64][127][210][211]. Wakes and eddies behind high-rise buildings can cause rapid vertical mixing of high momentum fluid and dominate the UCL–UBL interactions. Profiles of turbulence statistics, observed inside and above urban canopies, show high spatial variability horizontally and vertically. The turbulence kinetic energy (TKE) and turbulent shear stress have low values inside the UCL and pronounced peaks in the shear layer region developing above roof level. This is in good agreement with results for vegetation canopies and similar results of RSL turbulence found in full-scale urban studies (Section 3.2).

4.2 Statistical models

Statistical models allow easy estimation of the effects of cities on climate. Their main advantages are simplicity, which allows for approximation of meteorological parameters within the city; low computational requirements; a modest number of input parameters; and low risk of producing unrealistic results. The disadvantages of many (but not all) statistical models include limitation to the city (region, climate zone) in which they were developed; need for long observation periods or data from a large number of different locations; and lack of a physical basis.

The canopy urban heat island is the most intensively studied phenomenon and therefore many statistical models have been developed [212][213][214][215][216][217][218][219][220][221][222][223][224][225][226][227]. Many are simple linear (multiple) regressions of temperature differences between the city centre and the surrounding rural area, ΔT, as a function of meteorological variables such as wind speed, rural lapse rate, etc. [212][228][229][230][231][232][233]. More sophisticated statistical models use spectral analysis, eigenvectors or neural networks [233][234][235][236]. They often work well for the city in which they were developed and can be useful for local authorities to predict risks related to UHI (like amplification of heatwaves by that city).

Statistical relations have been used to determine the normalized UHI evolution which allows for fast (operational) forecasts of city temperatures [215]. This has been used to predict future climate conditions (with global or regional climate model outputs), and to correct historical records for urban effects. Very similar statistical relations with inputs including land cover information (for example, built fraction), have been developed to model intra-urban temperature distributions [237][238][239][240][241][242]. Statistical models of a city’s influence on other meteorological parameters are sparse and in the majority of cases reduced to regression analysis against meteorological, topographical or urban parameters. Statistical models of radiation fluxes have proved fairly useful [243][244][245][246]. Availability of incoming short-wave radiation allows modelling of net all-wave radiation by simple linear regression. Net and upward short-wave fluxes can be estimated if the surface albedo is specified. Absorbed short-wave radiation can be used in correction factors to calculate upward long-wave radiation when the surface temperature is replaced by standard near-ground air temperatures [247].

Turbulent heat fluxes can be expressed as a fraction of net all-wave radiation and the storage heat flux as a derivative of net radiation to capture hysteresis phase-lags between the two fluxes [248][249]. The objective hysteresis model (OHM) is a generalization of this approach which incorporates both the hysteresis nature of the storage heat flux and the surface properties of the city [164][250]. These models form part of the local-scale urban meteorological parameterization scheme (LUMPS) which requires only meteorological parameters (solar radiation, air temperature and humidity, atmospheric pressure) and surface descriptors to model turbulent (sensible and latent) and storage fluxes [247][251].

4.3 Numerical Models

4.3.1 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) models cover a wide range of numerical models from Reynolds-averaged Navier-Stokes (RANS), through Large Eddy Simulation (LES) to Direct Numerical Simulation (DNS) in terms of increasing computer needs. These models make a variety of assumptions to allow flows to be calculated at the microscale. There are now commercial CFD codes available which have been used to simulate flow over and inside street canyons with additional modifications to examine the transport of reactive air pollutants [252][253][254][255][256]. Examples are CFD-Urban, FLACS, Fluent-EPA, FEFLO, and FEM3, which were included in a CFD model comparison exercise for Manhattan by Hanna et al. (2006*a*, 2006*b*). Model evaluation efforts and inter-comparison studies for European CFD models are summarized in Sahm et al. [258] and Ketzel et al. [257]. Most CFD models use the RANS equations, which imply a steady-state solution [257][258](Hanna et al., 2006*a*, 2006 The CFD models require input of a good meteorological profile on the upwind edge of their geographic domain, which is usually 1 to 5 km on a side. It is found that there is a need to adjust model parameters to assure that sufficient turbulence is generated by the model, and to account for meandering of the input wind field. The urban-adjusted CFD models do produce reasonable agreement with field observations and allow the flow patterns around specific buildings to be seen, such a large eddies in the lee of tall buildings.

Large Eddy Simulation is becoming more widely used. In the LES approach, the large-scale, energy-carrying eddies are explicitly resolved under unsteady and intermittent flow conditions while smaller scale eddy activity is parameterized. Initial applications were restricted to flow in simple two-dimensional street canyon structures. Large Eddy Simulation studies have modelled pollutant flux transport along a street canyon at roof level and used wind tunnel measurements to assess performance [259][260][261][262]. Pollutant exchange rates, pollutant concentration and retention times to compare ventilation and air quality conditions in street canyons over a range of aspect ratios have been calculated [263][264][265][266][267]. Large Eddy Simulation produces realistic results for flow and pollutant transport in narrow, simple two-dimensional street canyons (aspect ratio between about 0.3 and 10, that is, skimming flow) under neutral conditions, including simple air pollution chemistry (NO-NO_2-O_3 mechanism).

Improved computer power has led to the development of LES models capable of dealing with simple three-dimensional built configurations (for example, So et al. [268]). Large Eddy Simulation has been used to investigate the role of plan area density (λp) within three-dimensional street canyon mean wind speeds [269]. Wind speeds were found to be 2–3 times higher in the sparse urban configuration. Similarly, LES has been used to compare flow in aligned and staggered arrays of cubes, with varying densities and building heights [270][271]. Drag in the staggered arrays is sensitive to λp but not for aligned ones. Moving from uniform to non-uniform building height drastically increases the drag and changes the flow coherence [272]. Direct Numerical Simulation approaches are also beginning to be pursued [273][274][275].

The complicated nature of real world cities has constrained the number of numerical studies of flow over complex and realistic geometry [272][276][277][278][279]. Solving the flow explicitly in the canopy layer remains challenging due to computer memory and speed demands. One approach that is currently being actively developed is that of nesting CFD codes into mesoscale models [280][281]. At the mesoscale, parameterizations have been included to model the effect of land surface on the dynamics in the Atmospheric Boundary Layer by LES [282][283].

4.3.2 Parameterizations

Increases in computing capability, which allow greater spatial resolution within numerical models, have been accompanied by a surge in the number of parameterizations of urban surface–atmosphere exchanges. Many groups interested in different applications have developed models to incorporate urban features, ranging from global climate modelling, numerical weather prediction, air quality forecasting and dispersion modelling to characterizing measurements, understanding heat island circulations and water balance modelling [56][58][66][67] [284][285][286][287] [288][289][290][291][292][293][294]. There are more than 40 schemes incorporating a wide range of urban features such as surface morphology, presence of impervious materials, vegetation cover and anthropogenic heat, all of which have a significant effect on the urban climate and need to be included, if the computational requirements are not excessive. These models can be classified in a number of ways including which fluxes they actually calculate [295][296].

Many of the urban land surface parameterizations have been evaluated against observations (for example, Grimmond and Oke [251]; Masson et al. [297]; Dupont and Mestayer [298]; Hamdi and Schayes [299]; Krayenhoff and Voogt [293]; Kawai et al. [300]). Currently an international model comparison is being conducted, in a controlled manner, that allows robust model intercomparison by class [295][296]. Early results demonstrate that inclusion of vegetation is important, even in dry environments. Models have greatest ability to model net all-wave radiation. Participation in the model comparison has resulted in improved simulation capability in these models in general, which points to the importance of such international collaborations.

4.4 Dispersion and air quality models

Improving public health and safety of urban dwellers requires improved ability to characterize and predict urban air quality (chemical weather) which, like physical processes, is impacted by variability at a range of space and timescales [301]. This involves both observations and models, and their close integration. The use of chemical weather forecasts in public health and safety management is new. For example, Air Quality Forecasting System for Australian cities (AAQFS) since 2000; RAMS/BRAMS has run operationally in Brazil since 2004 and more recently in other South American countries (for example, Peru and Chile) [302]. Many cities around the world provide real-time air quality/chemical weather forecasts, and several national services are broadening to include prediction of environmental phenomena such as plumes from biomass burning, volcanic eruptions, dust storms and urban air pollution that could potentially affect the health and welfare of their inhabitants. Such alerts can help reduce acute exposure when high pollution levels are expected. Routine daily forecasts enable the public to make healthier choices (for example, exercising outside only on low pollution days). Chemical weather forecasts enable business organizations to schedule their activities more effectively to reduce emissions on predicted high-pollution days, to reduce the cost of continuous emission controls.

Urban dispersion models range from very simple single equation models that parameterize the urban boundary layer and its controls on dispersion, to very complex CFD models that have the potential to calculate with high precision and resolution. Applications range from estimates of long-term health effects to short-term emergency response. The spectrum of models is widening rapidly due to the demand, the availability of tracer observations to test the models and the availability of three-dimensional high resolution (< 1 m) information on urban geometry.

The complexity of urban dispersion models has been driven by computer speed and storage capacity. Early Gaussian plume models applied to cities used rural parameterizations of stability, adjusted towards neutral conditions and larger dispersion coefficients [303][304]. Other simple adjustments for urban land use have included increased surface roughness length, decreased albedo, etc. These approaches have been used in gridded meteorological models such as the fifth generation National Center for Atmospheric Research/Pennsylvania State University Mesoscale Model (MM5) and urban airshed models to study ozone formation [305]. Today, urban dispersion is simulated typically using CFD models, models generating a mass-consistent wind field and using a Lagrangian particle dispersion model (LPDM), street-canyon models designed to reproduce the complex dispersion patterns observed in narrow street canyons or Gaussian plume models using specific building geometry [156][157][195][257][258][306][307][308][309][310].

Other dispersion models parameterize the urban surface and boundary layer, include urban wind profiles or combine with three-dimensional meteorological forecast models [312][313][314][315][316]. Simple Gaussian-based urban dispersion models also parameterize low wind speeds, high turbulence intensities and the known tendency towards neutral conditions in urban areas [317][318][319][320][321]. They perform adequately against urban field observations of tracer dispersion and often perform as well or better than more complex models [322].

All dispersion models should incorporate a meteorological model or parameterization scheme to account for ubiquitous urban effects such as the slowing of winds, the increase of turbulence, the vertical profile of meteorological variables in the urban canopy layer, and the tendency towards neutrality due to mechanical mixing. The thermal structure and depth of the urban mixing layer is also needed for plumes that have several kilometres of travel or are released above the urban canopy. Ideally urban dispersion models should also be able to account for changes in meteorological conditions between different urban districts.

5. Conclusions and assessment of gaps and recommendations for the next decade

This paper focuses on current capabilities to observe and predict urban atmospheric processes across a range of spatial scales. A wide range of applications use urban meteorological information. These range in scale from architectural design of the individual building to the whole city and its impact on the region, and to the role that cities and their inhabitants have on global changes in atmospheric composition and climate variability. The data needs, predictions and process understanding range from the protection of the inhabitants from short-term meteorological events such as intense rainfall through extremes of weather such as caused by heat stress enhanced by the urban heat island, and on to the long-term impacts of building design and urban planning and the role of transportation network design on air quality and health. Thus there are important social, economic and health benefits of an enhanced understanding of urban meteorological processes from the timescale of seconds (for example, chemical dispersion) to 100 years (for example, the lifetime of buildings) to 1 000 years (for example, city-scale planning). Awareness of current scientific capabilities and understanding based on observations and modelling is essential. Here these are reviewed and the main areas where improvements in our capabilities are needed for the design of more sustainable cities are identified.

The following are identified as areas where improvements in our capabilities are needed to ensure that in the next 10 years we actively move towards developing more sustainable cities. Each is given a high (H), medium (M) or low (L) ranking.

Observations

(a) Need operational urban meteorological networks (within and around the city) with optimum balance between resolution and practicability, networks that include surface-based instrumentation (soil moisture and air/soil/surface temperature), and vertical profiles (from within the deep urban canopy layer to the top of the boundary layer) of temperature, humidity, wind, turbulence, radiation, rainfall, air quality (gases and particles, precursors and secondary), reflectivity and refractivity. (H)

(b) Need observations over and within a larger range of urban morphologies to establish universal flow and flux characteristics. Need to ensure that there are long-term datasets (rather than short-term campaigns) that have wide spatial representativeness. The existing long-term measurement stations should be preserved. (H)

(c) Need to measure fluxes of CO_2 using eddy covariance approach combined with isotopic analysis to determine not only the sizes of these fluxes but also to identify emission sources (for example, background concentration, gasoline combustion, natural gas combustion and respiration) to evaluate the role of cities on the earth–atmosphere carbon exchange. (H)

(d) Need to undertake measurement studies to validate quantitative estimates of anthropogenic heat and moisture emissions and improve estimation techniques at a range of scales starting with the individual building where measurements can close the energy budget of a control volume. (M)

(e) Need simultaneous measurements of flow properties at various sites and levels to better study coherent structures and intermittent ventilation processes within the RSL. (M)

(f) Need to better assess urban surface characteristics (for example, emissivity to develop methods to correct for thermal anisotropy), and determine fluxes from remote sensing. (M)

(g) Need to explore the use of new measurement techniques including the use of remote-sensing technologies and smaller, more mobile and affordable instruments. (M)

Data

(a) Need to meet data requirements to allow translation of research findings into urban/building design tools and guidelines for different climate zones and classes of urban land use. (H)

(b) Need to ensure that data are provided in a format that is usable for a broad range of practitioners without compromise to scientific accuracy and integrity. (H)

(c) Need to ensure metadata to describe instrument, siting, quality assurance and control features and documentation are complete and comparable by creating and using a standardized urban protocol. (H)

Understanding

(a) Need to develop methods and frameworks to analyse atmospheric data measured above complex urban surfaces. This includes measurement source areas to ensure representative results and meaningful comparison between sites. (H)

(b) Need to know more about the outer layer of the UBL, that is, the atmosphere above the ISL. (H)

(c) Need to assess for each intervention what scale interventions are needed and possible (for example, legally, economically, planning, technically, etc.) to make cities more sustainable (liveable, healthy, etc.). (H)

(d) Need for assessment of human-induced large-scale climate change at the scale of cities to ensure that the signal of climate change is distinguished from the noise of natural variability. (H)

(e) Need to better understand the coupling of surface and air temperatures. (M)

(f) Need to examine ventilation and pollutant removal mechanisms (upward and sideward) for three-dimensional street canyons. (M)

(g) Need to understand if urban canopies are a special class of rough wall or canopy flows, and to what extent urban RSL turbulence can be described with a possibly modified mixing layer model. (M)

(h) Need to increase our knowledge on the subsurface heat island. (L)

Modelling

(a) Need to evaluate urban land surface schemes in both offline and online mode for a wide range of conditions to ensure that the models are fit for purpose. (H)

(b) Need to improve short-range, high-resolution numerical prediction of weather, air quality and chemical dispersion in the urban zone through improved modelling of the biogeophysical features of the land surface and consequent exchange of heat, moisture, momentum and radiation (the surface energy balance) with the UBL. (H)

(c) Need CFD/LES studies of wind and pollutant transport in regimes other than skimming flow and with combined effects of wind and buoyancy. (H)

(d) Need to improve understanding of feedback mechanisms between the urban environmental conditions and human activity. (H)

(e) Need to incorporate more realistic air pollution chemistry mechanisms (for example, O_3 titration at urban canopy level) into models. (M)

(f) Need to further develop multiscale modelling to allow investigations such as the effect of large-scale atmospheric turbulence on the neighbourhood or microscale turbulence below the canopy levels; the interaction between natural and artificial landscapes; the assessment of street-level comfort; building energy consumption; and urban design. (M)

(g) Need laboratory and CFD/LES studies with structures that more closely resemble cities than earlier, idealized homogenous arrays to inform model development for urban RSL turbulence. (M)

(h) Need further work on a simple universal UHI model for applied users (for example, extensions from Oke [215]). (L)

Tools

(a) Need to develop tools to allow models to be able to accommodate the wide differences in data availability depending on the application from research to operational situation. For example, in field research studies, extensive wind observations may be available (and detailed building morphology), but for emergency response situations only minimal inputs may be available (for example, winds from the nearest airport, no three-dimensional building data). (H)

(b) Need to develop designs that promote shading and ventilation without compromising air quality and natural lighting for hot cities. (H)

(c) Need to encourage development of active simulation tools (for example, www.susdesign. com/tools.php) through community participation (for example, forums, blogs, wikis). (H)

(d) Need to develop tools that allow competing and unintended impacts of proposed sustainable design to be assessed (for example, will urban greening reduce temperatures but increase humidity, resulting in no net increase in comfort levels?). (H)

(e) Need to develop tools that allow assessment of the best, or the ranking of, social, economic and environmental decisions for urban climate management (for example, urban greening vs. repaving roads and pavements with high(er) albedo vs. low-emissivity materials vs. limiting the contribution of anthropogenic heat; investment in expensive multi-functional solutions (for example, vegetated roofs) vs. cheaper, single benefit solutions such as cool roofs). (H)

(f) Need to make use of spatial and temporal estimation of transport emissions through vehicle fleet efficiencies and traffic data. (M)

(g) Need to solve technical challenges such as moisture seepage in vegetated roofs, and hazards to street trees (for example, pests, new pathologies, soil quality, compaction, drainage, frequent disturbances from utility trenches and excessive paving). (M)

(h) Need to determine how to link the beneficiaries of urban climate interventions with the costs of implementing them. (M)

Education

(a) Need to ensure widespread education of the meteorological community of the needs for planning and managing cities of all sizes in an as sustainable manner as possible. (H)

(b) Need to encourage communication which crosses traditional scientific discipline and spatial scale (for example: http://www.conservationeconomy.net ; http://www.sustainable-buildings. org/index.php). (H)

(c) Need to improve public education and communication of heat/health perception through use of simple language and community access. (H)

(d) Need for collaboration with stakeholders in the widespread development of heat/health warning systems. (H)

(e) Need to communicate through conventional publications and to use current (and evolving) electronic media to allow accessibility with depth of content that is up-to-date. (M)

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